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Electrophysiological Evidence of the Capture of Visual Attention

Clayton Hickey[1], John J. McDonald[2], and Jan Theeuwes[1]

Abstract

■ We investigated the ability of salient yet task-irrelevant stimuli to capture attention in two visual search experiments. Participants were presented with circular search arrays that contained a highly salient distractor singleton defined by color and a less salient target singleton defined by form. A component of the event-related potential called the N2pc was used to track the allocation of attention to lateralized positions in the arrays. In Experiment 1, a lateralized distractor elicited an N2pc when a concurrent target was presented on the vertical meridian and thus could not elicit lateralized components such as the N2pc. A similar distractor-elicited N2pc was found in Experiment 2, which was conducted to rule out certain voluntary search strategies. Additionally, in Experiment 2 both the distractor and the target elicited the N2pc component when the two stimuli were presented on opposite sides of the search array. Critically, the distractor-elicited N2pc preceded the target-elicited N2pc on these trials. These results demonstrate that participants shifted attention to the target only after shifting attention to the more salient but task-irrelevant distractor. This pattern of results is in line with theories of attention in which stimulus-driven control plays an integral role. ■

INTRODUCTION

The human visual system is subject to a torrent of sensory information, with only a small subset of these data important at any given moment. In order for humans to act efficiently, relevant visual information must be preferentially selected via the application of attention. In our phenomenological experience, this process of attentional selection seems tied to particular tasks and challenges. We feel that we select information that relates to our goals and helps us make necessary decisions. In an apparent inconsistency, however, we also feel that certain stimuli have a fundamental ability to capture our attention. A flash of light, a bright color, or the appearance of a moving object leaves us with the idea that we can not help but attend to these events, regardless of their relevance to our immediate goals.

In the field of vision research, these two experiences correspond to two conceptualizations of attentional control. On the one hand, we can think of attention as being under *goal-driven* control, oriented to objects and events that are relevant to the current goals of the observer. Alternatively, we can consider attention under *stimulus-driven* control, oriented to salient environmental stimuli. A vast amount of prior research has examined the ways in which these two types of control processes interact. Within this literature, an important and ongoing debate has arisen concerning the ability of stimuli to elicit a purely stimulus-driven orientation of attention to their location. This phenomenon is known as *attentional capture* (see recent reviews, e.g., Rauschenberger, 2003; Ruz & Lupiañez, 2002; Theeuwes & Godijn, 2002; Yantis, 2000).

In the early 1990s, Theeuwes (1991, 1992, 1994a) presented data from a series of visual-search experiments that were consistent with the notion of attentional capture. Participants were presented with *singleton* stimuli defined by a single featural difference from neighboring stimuli. In one experiment, participants were presented with circular displays consisting either of six circles and a single diamond or six diamonds and a single circle (Theeuwes, 1991). The task was to discriminate the orientation of a line segment contained within the uniquely shaped stimulus. In addition to the shape singleton, an irrelevant color singleton was presented on half of the trials. Namely, one of the nontarget stimuli was red, whereas the others were green or vice versa. Critically, the presence of the irrelevant color singleton increased the time required to respond to the relevant form singleton. This response time (RT) cost led Theeuwes (1991) to theorize that the color singleton captured attention automatically because of its high level of saliency. Attention was thus oriented to the task-relevant shape singleton only after an initial shift of attention to the distractor was completed and this more salient stimulus was determined irrelevant.

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The RT cost associated with the presentation of an irrelevant singleton has been observed in the majority of studies using variants of the *additional singleton paradigm* described above (Bacon & Egeth, 1994; Theeuwes, 1991, 1992, 1994a, 2004). Whereas Theeuwes (1991, 1992, 1994a, 2004) has consistently proposed that this cost is a product of attentional capture by the highly salient distractor singleton, other researchers have provided interpretations that challenge this *automatic capture hypothesis*. Perhaps the strongest alternative was proposed by Folk and Remington (1998), who suggested that the RT costs observed in the additional singleton paradigm are a product of filtering costs, similar to those reported in Kahneman, Treisman, and Burkell (1983). By this idea, the inclusion of a salient nontarget in the stimuli array increases the complexity of the visual search display, with a corresponding increase in preattentive processing requirements. This additional processing takes time and thus delays shifts of attention to the target. Crucially, this *contingent capture hypothesis* does not rely on automatic orientation of attention to the nontarget singleton to explain increases in RT. Rather, the theory proposes that top-down attentional set allows for highly salient nontarget stimuli to be effectively ignored, so long as these irrelevant stimuli are defined in a featural dimension different from that of the target (Folk & Remington, 1998; Folk, Remington, & Wright, 1994; Folk, Remington, & Johnston, 1992).

The present study was designed to determine whether task-irrelevant singletons do, in fact, capture attention. To date researchers have investigated this issue by observing the effects of irrelevant singletons on behavioral responses to task-relevant stimuli. There are two limitations to this approach. First, capture by the irrelevant singleton must be inferred indirectly because no behavioral response is made to that stimulus. Second, modulations in behavioral performance indicators such as RTs may result from processing changes at any number of stages. Thus, it is difficult to determine whether the appearance of an irrelevant singleton influences processing of the target singleton at early perceptual stages, as would be expected if the irrelevant singleton introduced perceptual filtering costs; at mid-latency attentional stages, as would be expected if the irrelevant singleton captured attention; or at later post-perceptual stages, as would be expected if the irrelevant singleton biased response. To distinguish between these possibilities, we recorded event-related potentials (ERPs) from participants while they performed a visual search task. ERPs are scalp-recorded voltage fluctuations that reflect moment-to-moment changes in neural processing. As such, they provide a means of evaluating the time course of activity related to different stages of perception and can be used to investigate the processing of both task-relevant stimuli and task-irrelevant stimuli.

To investigate whether salient but irrelevant stimuli capture attention, we focused on a specific component of the visual ERP that has been linked to the deployment of attention in visual space (Woodman & Luck, 1999, 2003; Luck & Hillyard, 1994a, 1994b). This component, known as the N2pc, is a negative-going deflection that is observable in the ERPs recorded over the posterior scalp roughly 175–300 msec poststimulus. Specifically, the N2pc is defined as a larger negative voltage at electrodes contralateral to an attended stimulus than at electrodes ipsilateral to that stimulus, and is named for its polarity, latency, and topography (posterior contralateral negativity in the latency of the N2 component). The N2pc is thought to reflect the attentional selection of an item in a search array via the suppression of surrounding items (Luck, Girelli, McDermott, & Ford, 1997; Luck & Hillyard, 1994b; see Eimer, 1996, for a different attentional explanation), a hypothesis that is supported by results showing that the target-elicited component is larger in amplitude when surrounded by highly salient distractor stimuli (e.g., Hopf, Boelmans, Schoenfeld, Heinze, & Luck, 2002; Luck et al., 1997). Because it is closely associated with attentional processes, the N2pc has been widely used as a tool to study the deployment of attention in visual space.

In each of two experiments reported below, participants were presented with visual search arrays that contained a target shape singleton and, on some trials, an irrelevant color singleton. As in the design used by Theeuwes (1991), the irrelevant color singleton was designed to be more salient than the target shape singleton. Following the well-documented RT cost associated with the presence of highly salient distractor singletons, we expected to find delayed responses to the target when the irrelevant color singleton was present. The N2pc component was then isolated in order to chronicle the spatial deployment of attention following the presentation of the search arrays. Our strategy was to compare the N2pc elicited by several different types of search arrays, including those containing (1) a lateralized target and no distractor, (2) a lateralized target and a contralateral distractor, (3) a vertical target and a lateralized distractor, and (4) a vertical distractor and a lateralized target. By including trials on which either the distractor or target singleton was presented on the vertical meridian, we were able to independently measure the allocation of attention to the two stimuli using a method introduced by Woodman and Luck (2003). This method relies on the fact that stimuli on the vertical meridian do not elicit the N2pc. Thus, by presenting one singleton on the vertical we were able to determine whether the other, lateralized singleton elicited the N2pc.

Following our general strategy, we considered a number of predictions stemming from the automatic and contingent capture hypotheses. If the automatic capture hypothesis is valid, attention should be initially oriented

to the location of the distractor followed by a reorientation to the location of the target. Thus, when the target and distractor singletons are presented on opposite sides of fixation, the ERP waveform should initially be more negative at electrodes contralateral to the distractor (i.e., a distractor-elicited N2pc) only later becoming more negative at electrodes contralateral to the target (i.e., a subsequent target-elicited N2pc; cf. Woodman & Luck, 2003). Furthermore, given the automatic capture of attention by the distractor singleton, we should be able to observe a distractor-elicited N2pc in conditions in which the target singleton is presented on the vertical meridian of the visual search display.

In contrast, if the contingent capture hypothesis is valid there should be no distractor-elicited N2pc in any experimental condition. Instead, variation in the onset of the target-elicited N2pc should be apparent. Specifically, the target-elicited N2pc should onset later in time in conditions in which the salient distractor is present, reflecting a delay in the orientation of attention. Additionally, if the N2pc is an index of distractor suppression (cf. Hopf et al., 2002; Luck et al., 1997), a larger target-elicited N2pc should be evident when a salient distractor is present.

EXPERIMENT 1

Methods

Participants

Eighteen healthy students of the Vrije Universiteit Amsterdam gave informed consent before beginning Experiment 1. All subjects reported normal or corrected-to-normal vision and normal color vision and were paid for their participation. Data from two participants were discarded due to excessive eye movement artifacts in the electroencephalogram (EEG), and data from one participant were discarded as the N2pc was not evident in any experimental condition. Two of the remaining 15 participants (5 women; age 21 ± 2.4 years, mean ± *SD*) were left handed.

Stimuli

The primary experimental display was a visual search array consisting of 10 discrete shape stimuli, each presented equidistant (9.1°) from a central fixation point (see figures for examples). Shape stimuli were unfilled diamonds (4.2° × 4.2°) and circles (1.7° radius) with thin (0.3°) red or green outlines. A gray line (0.3° × 1.5°) randomly oriented either vertically or horizontally was contained within each of the shape stimuli. All stimuli were presented on a black background.

The color and shape of the 10 stimuli were randomly varied within the following confines. In every trial, one stimulus was different in shape than the other nine. This could mean that in a given trial a diamond was presented among circles, or that a circle was presented among diamonds. In 33% of total trials, this shape singleton was the only unique stimulus and was randomly presented to one of eight lateralized screen positions. In the remaining 66% of total trials, one of the nine identically shaped stimuli was of a different color than all other stimuli, either red among green stimuli or green among red stimuli. In one quarter of these trials (~17% of total trials) the color singleton was presented on the vertical meridian, whereas the shape singleton was lateralized. In another quarter of these trials, the situation was reversed, with the shape singleton presented on the vertical meridian and the color singleton lateralized. In the remainder of color-singleton-present trials (~33% of total trials), the shape singleton was randomly presented at one of eight lateralized positions with the color singleton randomly presented to one of four lateral positions in the contralateral visual hemifield.

Procedure

Experimental stimuli were presented on a CRT monitor located 60 cm from the observer's eyes. Each experimental trial began with the presentation of a fixation point for a random duration of 600 to 1600 msec, followed by the presentation of a visual search array. The visual search array remained on the screen until 100 msec after a response was made, at which point the next trial began. Participant response was based on orientation of the line contained within the shape singleton. As line orientation was randomized, the target contained a vertical line in approximately half of trials and a horizontal line in the remainder.

Participants were instructed to respond as quickly as possible while maintaining an average accuracy of 90% or better, and feedback regarding accuracy and response latency was given at the end of each experimental block. Participants were instructed to maintain eye fixation throughout the experiment and were told that eye movements were being monitored. Each experimental block consisted of 48 trials, and each participant completed 30 experimental blocks, for a total of 1440 experimental trials per subject. Prior to beginning the experiment, each participant completed at least one practice block of 48 trials.

Responses were made via a custom-designed serial response box on which the left-hand button was separated from the right-hand button by 32 cm. Response mapping was counterbalanced across participants: Eight participants were required to respond with the left hand when the target line was vertical and with the right hand when the target line was horizontal, with the remaining participants given the opposite response map.

Recording and Analysis

EEG was recorded from 30 tin electrodes mounted on an elastic cap (Electro-cap International, Eaton, OH). Electrode positions were a subset of the international 10/10 system sites (FPz, F7, F3, Fz, F4, F8, C7, C3, Cz, C4, C8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO7, PO3, POz, PO4, PO8, O1, Oz, O2, Iz, and M2). The vertical electrooculogram (VEOG) was bipolarly recorded from electrodes above and below the right eye, and the horizontal electrooculogram (HEOG) was bipolarly recorded from electrodes 1 cm lateral to the external canthi. The VEOG was used in the detection of blink artifacts, and the HEOG was used in the detection of eye movement artifacts. All electrode impedances were kept well below 15 kΩ. All electrodes (except VEOG and HEOG) were referenced during recording to the left mastoid and were later digitally re-referenced off-line to an algebraic average of the left and right mastoids. The electrophysiological signals were amplified with a gain of 500 and a passband of 0.05–500 Hz, digitized at 500 Hz, and stored on a microcomputer. An automated artifact-rejection process was applied to the EEG in order to remove trials containing eye movement, blink, or amplifier-blocking artifacts. All trials containing such artifacts in a 1000-msec epoch beginning 200 msec before stimulus onset were rejected. The automatic rejection of trials containing eye movements was further verified via inspection of the averaged HEOG signal for individual participants. The averaged HEOG did not exceed 2 μV for any analyzed participant, which suggests that any eye movements contained in trials that were not rejected were less than 0.3° visual angle in size (see McDonald & Ward, 1999, for HEOG calibration). Following the creation of ERPs, a Gaussian finite impulse function (3 dB attenuation at approximately 40 Hz) was used to digitally low-pass filter the data, effectively removing high-frequency noise produced by muscle activity and external electrical sources. For statistical purposes, ERP amplitude was computed with respect to a 100-msec prestimulus period. This period was also used to calculate the baseline of the ERPs presented in the figures.

Table 1. Mean Correct Response Times (RTs) and Error Rates by Experimental Condition

Experimental Condition	*Mean RT (SD), msec*	*Error Rate (SD), %*
(A) Experiment 1		
Lateral target, vertical distractor	695 (93)	16 (6)
Lateral target, no distractor	588 (91)	14 (6)
Lateral target, contralateral distractor	666 (88)	16 (6)
Vertical target, lateral distractor	729 (92)	17 (6)
(B) Experiment 2		
Lateral target, vertical distractor	999 (156)	10 (5)
Lateral target, no distractor	689 (106)	8 (3)
Lateral target, contralateral distractor	970 (141)	10 (3)
Lateral target, ipsilateral distractor	1054 (169)	12 (5)
Vertical target, lateral distractor	1015 (149)	10 (4)

Results

Behavioral Results

A total of 16.4% of trials were excluded from analysis due to erroneous behavior, 1.0% due to excessively slow response (>2000 msec) and 15.4% due to incorrect response. A further 8.2% of trials were excluded due to eye movement artifacts in the EEG. Behavioral and ERP analyses were conducted on the remaining data.

Table 1A presents the RT and error rate data observed in each of the four conditions of Experiment 1. The interparticipant mean RT observed across distractor-singleton-present conditions was 691 msec, whereas the mean RT in the distractor-singleton-absent condition was 588 msec. This 103-msec difference was found to be statistically significant in a repeated measures analysis of variance (ANOVA) with a single factor for distractor presence (present, absent), $F(1,14) = 60.52$, $p < .001$. A similar analysis of error rates revealed that participants made fewer errors when the distractor singleton was absent (14.3%) than when it was present (16.3%), $F(1,14) = 10.99, p < .01$. The convergence of RT and accuracy data indicates that there was no speed–accuracy trade-off. These behavioral results closely parallel those observed in several previous studies of attentional capture (Bacon & Egeth, 1994, Experiment 1; Theeuwes, 1991, 1992, 1994a).

Electrophysiological Results

In order to examine the possibility that the observed RT difference was a product of the capture of spatial attention, we first examined the difference between the target-elicited N2pc found when visual search arrays contained only a lateral target singleton, and the target-elicited N2pc found when visual search arrays contained both a lateral singleton target and a contralateral singleton distractor (Figure 1A and B, respectively). In both conditions, the ERP waveforms at lateral occipital electrodes (PO7 and PO8) consisted of a series of positive and negative peaks oscillating at approximately 10 Hz,

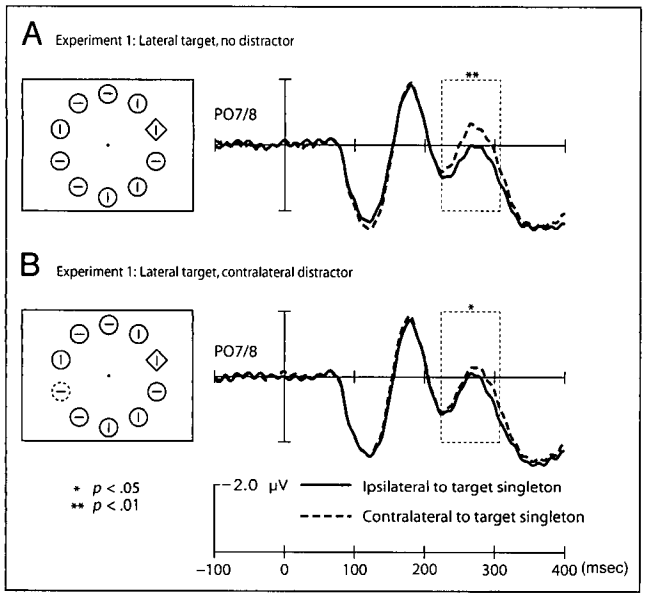

Figure 1. Grand-averaged ERPs elicited in Experiment 1 by circular search arrays containing (A) a lateral target and no distractor and (B) a lateral target and contralateral distractor. The distractor singleton, defined by color, is represented by a broken circle. Actual experimental stimuli were composed of color outlines on a black background. As with all ERPs presented in this article, these ERPs were recorded at posterior lateral electrode sites PO7 and PO8. Note that negative is plotted upwards, and that stimulus onset was at 0 msec.

including prominent P1 (120 msec), N1 (180 msec), P2 (230 msec), and N2 (280 msec) components.

As illustrated in Figure 1A, the P1 component was somewhat larger at posterior electrodes contralateral to the target than at posterior electrodes ipsilateral to the target when the search array contained a lateral target but no singleton distractor. A repeated measures ANOVA with electrode location (contralateral vs. ipsilateral, relative to the target) as the sole factor indicated that this laterality was statistically significant: 100- to 150-msec interval, $F(1,14) = 13.61$, $p < .01$. This may have been caused by an imbalance in sensory energy rather than an automatic capture of attention by the target (Luck & Hillyard, 1994a). As illustrated in Figure 1B, the P1 was laterally symmetric when the search array contained a lateral target and contralateral distractor: 100- to 150-msec interval, $F(1,14) < 1$.

The N2pc component was elicited by the lateralized target both when it appeared in the absence of a distractor singleton (Figure 1A), 225- to 310-msec interval, $F(1,14) = 17.41$, $p < .01$, and when it appeared with a distractor singleton in the opposite field (Figure 1B), 225- to 310-msec interval, $F(1,14) = 6.34$, $p < .05$. Visual inspection of the two ERPs suggests that the N2pc component was substantially smaller when an irrelevant distractor singleton was presented contralateral to the target (Figure 1B) as compared to when no distractor singleton was presented (Figure 1A). This pattern was confirmed by statistical analysis of the N2pc peaks. The mean ERP amplitude was measured in a 245- to 275-msec latency range at lateral occipital electrodes (PO7 and PO8) contralateral and ipsilateral to the target for both lateralized-target trials containing no distractor singleton and lateralized-target trials containing a contralateral distractor. A two-way ANOVA with repeated measures factors for electrode location (contralateral vs. ipsilateral, relative to target location) and contralateral distractor (present, absent) revealed a significant Location × Distractor interaction, $F(1,14) = 4.90$, $p < .05$, evidence that the observed reduction in N2pc amplitude between conditions was statistically reliable.

To independently examine the N2pc waves elicited by the target and distractor stimuli, we created separate ERPs for search arrays that contained either a target or distractor singleton on the vertical meridian (cf. Woodman & Luck, 2003). Figure 2A illustrates the ERP obtained when the distractor was presented on the vertical meridian and the target was presented to one of the eight lateralized positions, whereas Figure 2B illustrates the ERPs obtained when the target was presented on the vertical meridian and the distractor was presented to one of the eight lateralized positions. An N2pc can be observed contralateral to the target in Figure 2A, 230- to 290-msec interval, $F(1,14) = 5.28$, $p < .05$, and contralateral to the distractor in Figure 2B, 230- to 290-msec interval, $F(1,14) = 8.97$, $p < .01$.

Discussion

As is apparent in a comparison of Figure 1A and B and an examination of Table 1, the concurrent presentation of a distractor singleton to the visual hemifield contralateral to the target resulted in both an increase in response

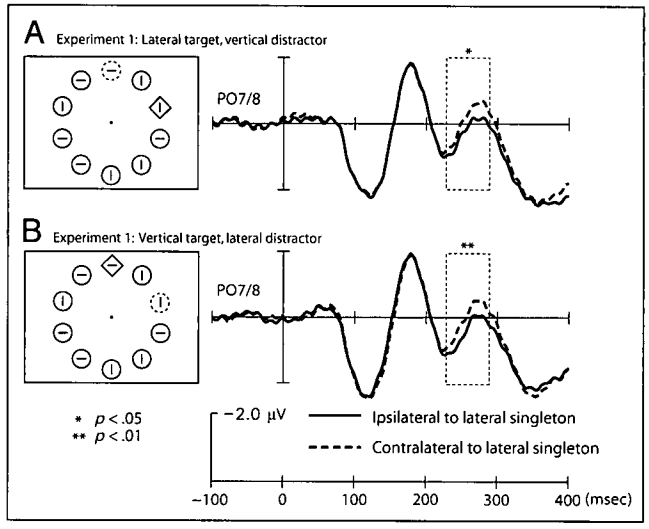

Figure 2. Grand-averaged ERPs elicited in Experiment 1 by circular search arrays containing (A) a lateral target and vertical distractor and (B) a vertical target and lateral distractor.

latency and a reduction in target-related N2pc amplitude. Furthermore, when only the distractor was presented to a lateral screen position, a distractor-elicited N2pc was apparent (Figure 2B). The presence of the distractor singleton did not, however, have any clear effects on the latency of the N2pc component. In Figure 1A and B, for example, the contralateral waveforms diverge from the ipsilateral waveforms at very similar latency points, and later converge at very similar latency points.

Although the results of Experiment 1 are generally supportive of the automatic capture hypothesis, they are not entirely conclusive. The existence of a distractor-elicited N2pc, as shown in Figure 2B, suggests that attention was often oriented to the irrelevant color singleton. If attention was invariably oriented to the distractor before the target, however, we would expect to observe a polarity reversal in the N2pc latency period when the target and distractor were presented in contralateral visual hemifields, reflecting an initial shift of attention to the distractor followed by a reorientation to the target. The absence of this pattern is puzzling.

One possible explanation for the lack of an N2pc reversal is that participants adopted a search strategy in which the distractor was used as a cue to the general location of the target stimulus. Adoption of such a strategy would have been less likely if the presentation of stimuli had been completely random, but this was not the case in Experiment 1. To maximize signal-to-noise ratios in the most critical experimental conditions (e.g., distractor-present trials), some other conditions were eliminated. Specifically, participants were never presented with visual search arrays in which the two singletons were on the same side of fixation. This resulted in a situation in which the distractor singleton, although not accurately predictive of target location, identified the visual hemifield to which the target *would not* be presented. This situation may have produced two undesirable effects. First, it may have counteracted the stimulus-driven processes that result in a strong capture effect, thereby reducing the distractor-elicited N2pc. Second, it may have facilitated the attentional engagement of the target, thereby increasing the target-elicited N2pc.

We conducted an additional experiment to control for the confound resulting from the elimination of same-hemisphere trials and to further test the predictions stemming from the automatic and contingent capture hypotheses. In Experiment 2, trials in which the target and distractor were in the same hemifield or in opposite hemifields were equally likely.

EXPERIMENT 2

Methods

Participants

Eighteen healthy students of Simon Fraser University gave informed consent before participating in Experiment 2. All reported normal or corrected-to-normal vision and color vision and received class credit for their participation. Data from two participants were discarded due to excessive eye movement artifacts in the EEG, and data from a further two participants were discarded as the N2pc was not evident in any experimental condition. All of the remaining 14 participants (6 women; age 21 ± 3.2 years, mean ± *SD*) were right handed.

Stimuli

The experimental stimuli used in Experiment 2 were identical to those in Experiment 1 with the following exception. In Experiment 2, the color singleton was presented in approximately 16% of total trials at one of three lateral positions in the same visual hemifield as the shape singleton.

Procedure

The experimental procedure used in Experiment 2 was identical to that in Experiment 1 with the following exceptions. In Experiment 2 responses were made via the left and right buttons on a standard computer mouse. Response mapping was not counterbalanced across subjects: All participants responded with their dominant hand (right in the case of all 14 analyzed participants), and responded with the left mouse button when the target line was vertical and the right mouse button when the target line was horizontal.

Recording and Analysis

EEG was recorded from 63 tin electrodes mounted in an elastic cap (Electro-cap International). Electrode positions were a subset of the international 10/10 system sites (FP1, FPz, FP2, AF3, AF4, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FC5, FC3, FC1, FCz, FC2, FC4, FC6, T7, C5, C3, C1, Cz, C2, C4, C6, T8, CP5, CP3, CP1, CPz, CP2, CP4, CP6, P7, P5, P3, P1, Pz, P2, P4, P6, P8, PO7, PO3, POz, PO4, PO8, O1, Oz, O2, I5, I3, Iz, I4, I6, SI3, SIz, SI4, and M2). The HEOG was bipolarly recorded from electrodes 1 cm lateral to the external canthi. The HEOG was used in the detection of eye movement artifacts, whereas electrode site FP1 was used in the detection of blink artifacts. All electrode impedances were kept well below 10 kΩ. All electrodes (except HEOG) were referenced during the recording to the left mastoid and were later digitally re-referenced off-line to an algebraic average of the left and right mastoids. The electrophysiological signals were amplified with a gain of 2000 and a pass-band of 0.1–100 Hz, digitized at 500 Hz, stored on a microcomputer, and averaged offline. All other analysis procedures, such as filtering and artifact rejection, were as in Experiment 1.

Results

Behavioral Results

A total of 10.2% of trials were excluded from analysis due to erroneous behavior, 0.8% due to excessively slow response (>2000 msec) and 9.4% due to incorrect response. A further 16.6% of trials were excluded due to eye movement artifacts in the EEG.

Table 1B presents the RT and error rate data observed in each of the five conditions of Experiment 2. The interparticipant mean RT observed across the distractor-singleton-present conditions was 1010 msec, whereas the mean RT observed in the distractor-singleton-absent condition was 689 msec. This 321 msec difference was found to be statistically significant, $F(1,13) = 409.50$, $p < .001$, and an analysis of error rates provided evidence that fewer errors were made when the distractor singleton was absent (present: 10.5%, absent: 7.5%), $F(1,13) = 26.61$, $p < .001$.

The pattern of behavioral results observed in Experiment 2 is roughly congruent with that observed in Experiment 1 in that participants were both slower and more error prone when the distractor singleton was present. Participants in Experiment 2 were generally slower but more accurate than those in Experiment 1 (see Table 1), suggesting that acceptable speed–accuracy trade-off rates differed between the groups.

Electrophysiological Results

Figures 3 and 4 present the ERPs elicited in the five conditions of Experiment 2. The ERP presented in Figure 3A was produced by trials in which the target stimulus was presented to one of eight lateralized positions and the distractor was presented to one of two positions on the vertical meridian. The ERP presented in Figure 3B was produced in the reverse situation, when the target was presented to one of two vertical positions and the distractor was presented to one of eight lateralized positions. When the distractor singleton was presented on the vertical meridian, the ERP to the search array was more negative at posterior electrodes contralateral to the target in the interval of the N2pc: 260–290 msec, $F(1,13) = 5.97$, $p < .05$ (Figure 3A). By comparison, when the target singleton was presented on the vertical meridian, the ERP to the search array was more negative at posterior electrodes contralateral to the *distractor* in the interval of the N2pc: 260–290 msec, $F(1,13) = 7.27$, $p < .05$ (Figure 3B). A two-way ANOVA with repeated measures factors of electrode location (contralateral vs. ipsilateral, relative to the lateralized stimulus) and condition (lateral target with vertical distractor vs. lateral distractor with vertical target) did not approach significance level, suggesting that the amplitude of the distractor- and target-elicited N2pc components are not reliably different: 260–290 msec, Condition × Location: $F(1,13) = 0.12$.

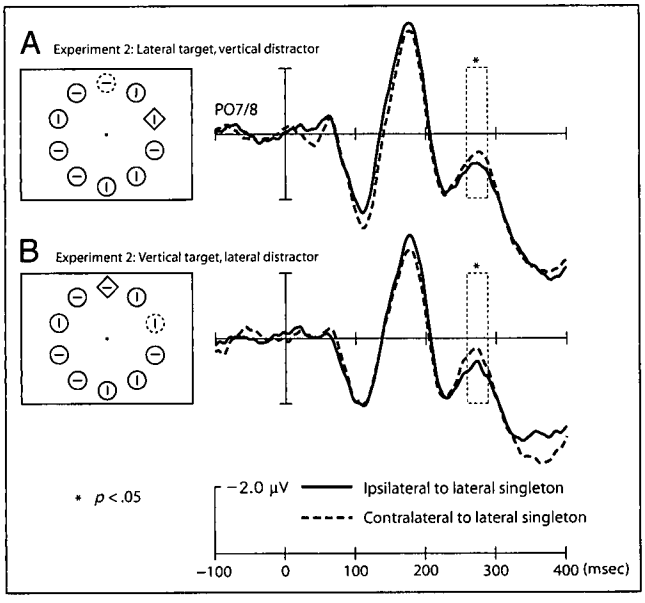

Figure 3. Grand-averaged ERPs elicited in Experiment 2 by circular search arrays containing (A) a lateral target and vertical distractor and (B) a vertical target and lateral distractor.

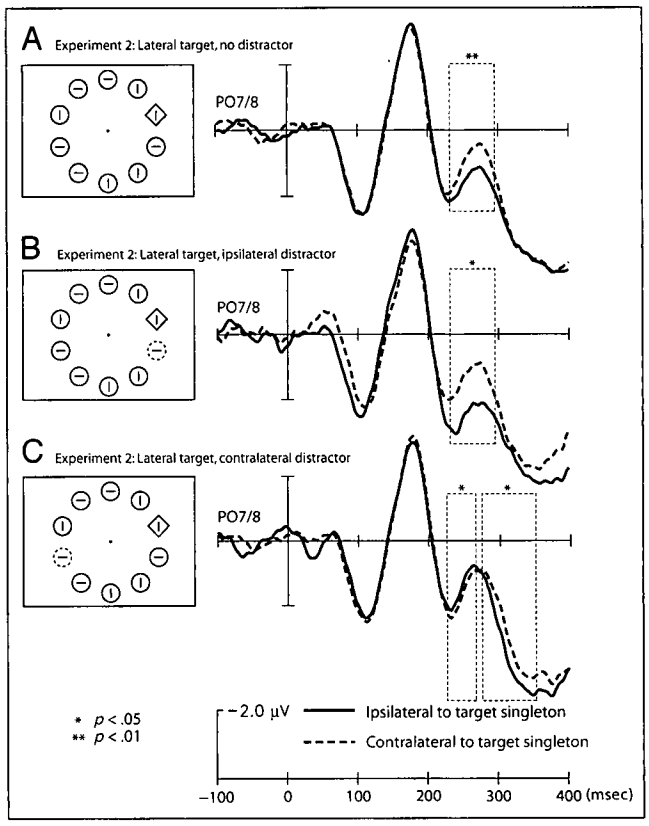

Figure 4. Grand-averaged ERPs elicited in Experiment 2 by circular search arrays containing (A) a lateral target and no distractor, (B) a lateral target and ipsilateral distractor, and (C) a lateral target and contralateral distractor.

Figure 4 shows ERPs elicited by the search array in the remaining three conditions. Search arrays that contained a lateralized target singleton elicited a posterior ERP negativity in the latency of the N2pc at electrodes contralateral to the target, both when the distractor was absent, 230–295 msec, $F(1,13) = 16.79$, $p < .01$, and when the distractor was on the same side of the vertical meridian, 230- to 295-msec interval, $F(1,13) = 4.66$, $p < .05$ (Figure 4A and B, respectively). In contrast, search arrays that contained a lateralized target and a contralateral distractor elicited a posterior ERP negativity in the latency of the N2pc that was initially contralateral to the *distractor* and only later contralateral to the target. The initial distractor-elicited N2pc was significant in the 220- to 265-msec interval, $F(1,13) = 7.10$, $p < .05$, and the subsequent target-elicited N2pc was significant in the 275- to 350-msec interval, $F(1,13) = 5.63$, $p < .05$, with the polarity reversal at approximately 270 msec.

To investigate the effect of distractor laterality on the magnitude of the target-elicited N2pc, we made a planned comparison between the target-elicited N2pc observed when a concurrent distractor was presented on the vertical meridian (Figure 3A) and the target-elicited N2pc observed when a concurrent distractor was presented in the same visual hemifield (Figure 4B). A two-way ANOVA with repeated measures factors of electrode location (contralateral vs. ipsilateral, relative to the target) and condition (lateral target with vertical distractor vs. both stimuli lateral to same visual hemifield) showed a significant interaction between the factors, indicating the target-elicited N2pc was larger when both the target and distractor were presented in the same hemifield: 245–255 msec, Location × Condition, $F(1,13) = 4.73$, $p < .05$.

Discussion

As in Experiment 1, a distractor-elicited N2pc was found in Experiment 2 when the target was presented on the vertical meridian. In addition, when the target and distractor were presented to opposite visual hemifields the N2pc was initially observed contralateral to the distractor, and only subsequently contralateral to the target (Figure 4C). The data thus suggest that attention was initially oriented to the distractor stimulus before being reoriented to the target, and provides compelling evidence for the automatic capture hypothesis. The absence of such an N2pc reversal in Experiment 1 indicates that the exclusion of some conditions in that experiment had a detrimental effect on the processes that generate the distractor-elicited N2pc.

The presence of a distractor in the same visual hemifield as the target can be observed to substantially increase the magnitude of the target-elicited N2pc in Experiment 2 (cf. Figures 3B and 4B), suggesting that a greater degree of distractor suppression was required when the distractor and target were presented close to one another (Luck et al., 1997). Note that this pattern was not observed in Experiment 1 when the target was presented to the contralateral visual hemifield (cf. Figure 1A and B); here, the presence of the distractor resulted in a *decrease* in target-related N2pc amplitude. This apparent inconsistency can be accounted for by the automatic capture hypothesis; when the target and distractor were presented to opposite visual hemifields in Experiment 1, attention was often directed to the distractor. When the N2pc elicited on these trials was averaged with the N2pc elicited in trials in which attention was directed to the target, the net result was a small target-related effect. The contingent capture hypothesis, in contrast, does not present an obvious solution to this pattern in the data.

The results of Experiment 2 provide one puzzle. Whereas the distractor-elicited N2pc observable in Figure 3B onsets at approximately 240 msec and offsets at approximately 290 msec, that observed in Figure 4C begins at approximately 220 msec and ends around 265 msec. This is the case even though regardless of whether our predictions are based on the contingent or automatic capture hypotheses, the pattern of attentional orientation in these two conditions should not differ. A post hoc repeated measures ANOVA was applied to the peak latencies of the distractor-elicited N2pc components in these two conditions in order to ascertain the reliability of the latency difference, $F(1,13) = 0.11$. The results leave open the possibility that the pattern is a product solely of chance. If the observed difference in N2pc onset does in fact have functional significance, it should be noted that it presents no challenge to the automatic capture hypothesis. If attention was initially oriented to the target when participants were presented with search displays containing a vertical target and lateral distractor (Figure 3B), engagement of the target would have occurred significantly earlier than can be observed when participants were presented with search displays containing a lateral target and contralateral distractor (Figure 4C). We would expect earlier engagement of the target stimulus to result in an RT advantage; in fact, mean RT in the vertical target, lateral distractor condition (Figure 3B) is 45 msec longer than that observed in the lateral target, contralateral distractor condition (Figure 4C). These results raise the possibility that the delay in orientation of attention to the distractor stimulus in Figure 3B created a subsequent delay in the orientation of attention to the target stimulus, which ultimately led to a slowing of manual response.

GENERAL DISCUSSION

The goal of the present study was to shed new light on a long-standing debate regarding the ability of salient nontargets to capture attention in visual search tasks. In both Experiments 1 and 2 we presented participants

with visual search arrays containing either a target singleton among low-saliency nontargets or both a target and distractor singleton among low-saliency nontargets in a design taken from the additional singleton paradigm (Theeuwes, 1991). Target and distractor singletons were defined by shape and color, respectively. Participants were required to respond to oriented lines contained within target singletons only; the distractor singletons, defined by color, were irrelevant to the task. Brain electricity was recorded using scalp EEG electrodes while participants completed the task, and the ERPs elicited by the search arrays were extracted from the EEG using standard signal averaging procedures. A particular component of the visual ERP that is known to reflect the spatial deployment of attention—the N2pc—was used to determine whether attention was captured by the irrelevant color singleton.

In both Experiments 1 and 2, responses were slower and more error-prone when a salient distractor was concurrently presented with the target. The ERP data demonstrated that this well-documented RT cost is due to attentional capture by the irrelevant target. In Experiment 1, the target-elicited N2pc component was smaller in magnitude when a salient distractor was concurrently presented with the target. Furthermore, a distractor-elicited N2pc was evident when the target was presented on the vertical meridian of the visual search display and, thus, was unable to elicit a lateralized N2pc (cf. Woodman & Luck, 1999, 2003). These results suggest that attention was often oriented to the distractor singleton. This is in spite of the fact that due to a confound in Experiment 1, the distractor singleton was predictive of the visual hemifield to which the target singleton *would not* be presented. In contrast, the presence of a distractor singleton was not found to result in latency shifts in the onset of the target-elicited N2pc, as would be expected if the initial orientation of attention were slowed by the presence of a distractor singleton.

The results of Experiment 1 are generally consistent with the automatic capture hypothesis. One important predicted pattern, however, is notably absent. Specifically, if, when both target and distractor were presented to opposite visual hemifields, attention was oriented to the distractor before the target, the ERP elicited in these trials should initially be more negative contralateral to the distractor singleton before reversing polarity to become more negative contralateral to the target singleton. The absence of this pattern in Experiment 1 suggests either that attention was captured in only a subset of total trials or that capture by the distractor was not consistently reflected in the N2pc.

One possibility is that the processes responsible for the distractor-elicited N2pc were somehow minimized in Experiment 1, possibly due to the unexpected adoption by participants of a search strategy based on distractor location. In Experiment 2, the ability of participants to adopt such a strategy was removed. The results of Experiment 1 were reproduced in Experiment 2. Furthermore, a clear distractor-elicited N2pc was observed to precede the target-elicited N2pc in Experiment 2 when the target and distractor were presented to opposite visual hemifields, a pattern predicted by the automatic capture hypothesis. Taken together, Experiments 1 and 2 provide strong support for the idea that salient nontarget stimuli capture spatial attention even when they are defined by an irrelevant visual feature.

It is important to point out that the displays used in the present study were not completely symmetric. On some trials, a singleton appeared on one side of fixation but not on the other, which would have caused a slight lateral imbalance in stimulus energy. Even when the target and distractor were both lateralized, there may have been some laterally imbalanced stimulus energy because the distractor singleton on one side was perceptually more salient than the target singleton on the other side. This leaves open the possibility that the distractor-elicited N2pc components observed in both Experiments 1 and 2 may have been caused by imbalanced stimulus energy rather than by shifts of attention. This alternative explanation can be assessed to some degree by determining whether the early sensory-evoked ERP components were lateralized. The results of Experiment 1 show that the early P1 component (100 msec) elicited by lateralized targets presented in the absence of distractors (Figure 1A) was slightly larger at occipital electrodes contralateral to the target. No hint of a lateralized P1 is apparent, however, in the ERP elicited when the target and distractor were presented on opposite sides of fixation. Consequently, although the larger N2pc on lateralized-target/no-distractor trials may have been caused in part by the difference in lateralized stimulus energy, the same cannot be said of the N2pc elicited on lateralized-target/lateralized-distractor trials because this ERP does not show any stimulus-induced lateral asymmetries prior to the N2pc latency range. This same reasoning applies to the other ERPs presented in the study. The general absence of early laterality, particularly in the ERPs in which a distractor-elicited N2pc is apparent, argues against a nonattentional interpretation of the results.

The results reported above are in line with other electrophysiological research providing evidence of the involuntary orienting of attention to task-irrelevant stimuli. It is now known that sudden but spatially nonpredictive cue stimuli not only facilitate overt responses to subsequent visual targets appearing nearby but also modulate target-elicited ERP activity in sensory cortical areas (for recent reviews, see Spence & McDonald, 2004; Hopfinger & Mangun, 2001). Such effects occur even when attention is captured by a cue in another task-irrelevant modality (McDonald, Teder-Sälejärvi, Di Russo, & Hillyard, 2003; Kennett, Eimer, Spence, & Driver, 2001; McDonald, Teder-Sälejärvi, & Hillyard, 2000; McDonald & Ward, 2000). These results, along

with those reported in the current study, suggest that stimulus-driven control processes play a very important role in the control of visual attention and provide evidence for models of attention in which these control processes play an integral role (e.g., Theeuwes, 1994b; Koch and Ullman, 1985).

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